Optical testing of MISR lenses & cameras

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ABSTRACT

A unique, highly automated thermal-vacuum facility for optical testing of lenses anti cameras is described. In particular, measurements of MTF, boresight, and geometric image distortion over a large parameter space including wavelength, field of view and temperature will be discussed. Unique aspects of the facility include a "virtual nodal bench" opto-mechanical metrology system and fiber-optic illumination of mechanical reference features.

Keywords: lens testing, MTF, nodal point, distortion

1. INTRODUCTION

JPL's Multi-Angle Imaging Spectro-Radiometer (MISR) instrument flying on the EOS AM 1 platform is scheduled to be launched January 1998. This CCD camera-based instrument has been designed to study (from low-Earth orbit) the ecology & climate of the Earth through the acquisition of systematic, global multi-angle imagery in reflected sunlight.

The MISR science instrument uses nine cameras employing four distinct lens designs. These cameras are pointed at nine discrete view angles relative to instrument nadir and form images with high geometric & radiometric fidelity. Complete 2D images from each camera will be built-up in pushbroom fashion as the instrument orbits the Earth. Within all nine cameras, four parallel CCD line arrrays will collect data in four ~30 mn-wide spectral bands centered at 443, S50, 670 and 865 nm.

The lenses & cameras to be tested all operate at infinite conjugates, at f/5.5, and over temperatures between 0°C and 10°C. Four distinct lens designs have the following first-order parameters:

		lens type A	lens type B	lens type C	lens type D
EFL	(mm)	59.3	73.4	95.3	123.8
FOV	(degrees)	±14.9	±12	±9.4	±7.3

2. NOMENCLATURE

"**MISR optical bench**" herein refers to the aluminum chassis onto which all MISR cameras are fastened.

"**Lens**" herein refers to assembly of individual lens elements in an aluminum lens barrel which includes a front mounting flange (for mounting to the MISR optical bench) and a shimmable rear adjustment flange (for mounting interchangeable CCD camera heads)

"**CCD camera** head" here refers to the assembly of MISR CCD detector array and associated electronics. Note one MISR CCD camera head design serves all MISR lenses.

"**Camera**" here refers to an assembly of the above two items.

"**MTF** head" here refers to an assembly of microscope objective and metrology CCD on a three-axis motorized & encoded stage. This piece of ground-based instrumentation is used to measure imaging performance of lenses.

As an assembled MISR camera includes no focus adjustment mechanism, prior to integration of the camera assembly onto the MISR optical bench, the camera assemblies must all be carefully pre-focussed & tested on the ground so as to insure performance over the entire operational envelope of wavelength, field and temperature.

3. PROJECT OBJECTIVE

In order to quantitatively characterize the imaging performance of all prototype & flight article MISR lenses and lens/can~cra systems, wc have designed and acquired a highly automated, self-contained, visible-tmncar-lK lens & camera optical characterization bench (OCB) system suitable for usc in a thermal vacuum test chamber. General & specific constraints & performance requirements placed on the OCB arc detailed below:

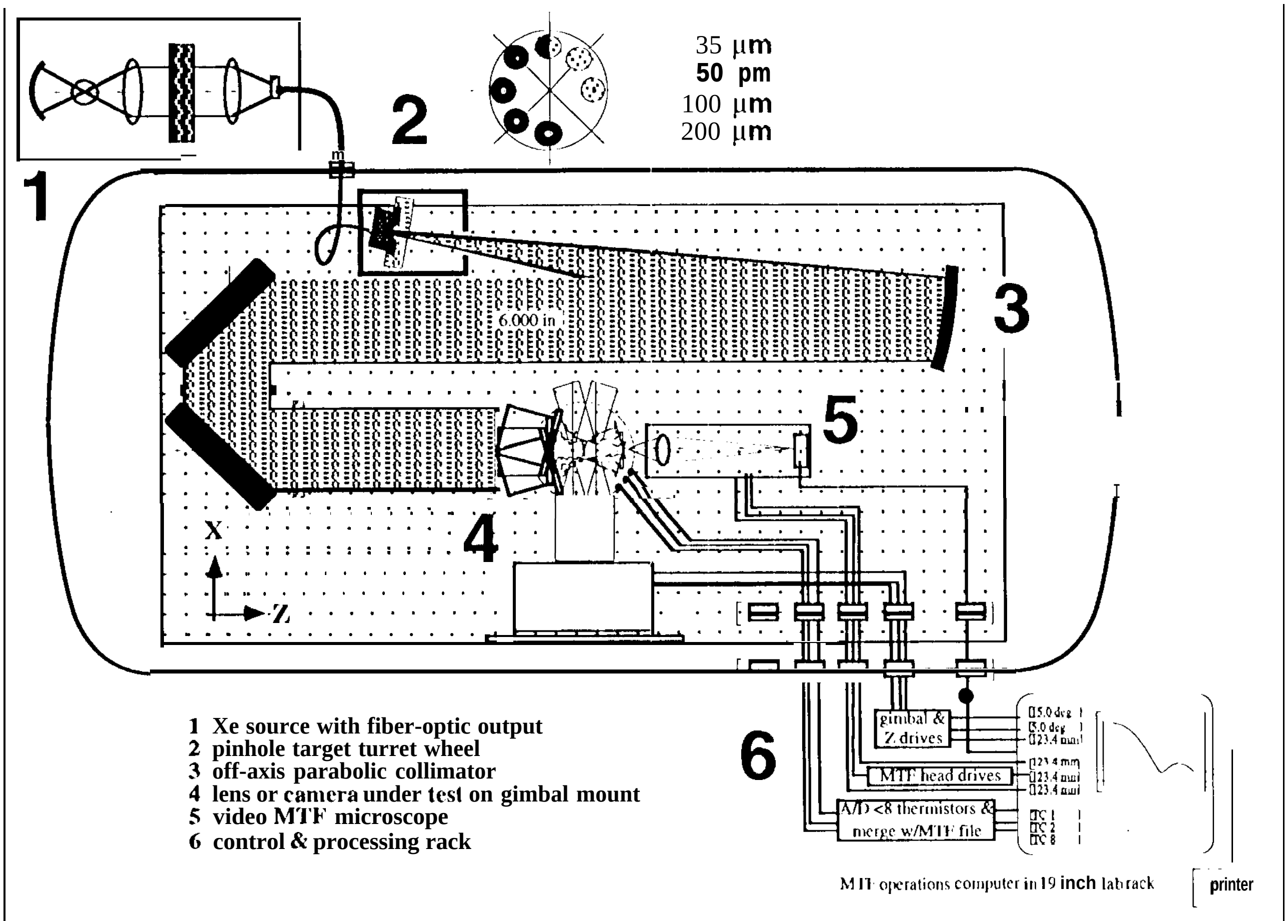
Operational Constraints

packaging/envelope	1.2 m diam. x 1.5 m vacuum chamber
wavelengths	400-900 nrn
test temperatures	-50°C -> +60°C
vacuum	10-6 torr
f-number	f/5.5
focal lengths	59- 124 mm
FOV	± 20 deg (max)
mass	5 kg (max)
cleanliness	minimum outgassing

Performance Requirements on test facility

lens & camera test configurations

MTF, boresight, distortion, transmission, stray light tests



OPTICAL CHARACTERIZATION BENCH DESIGN SCHEMATIC

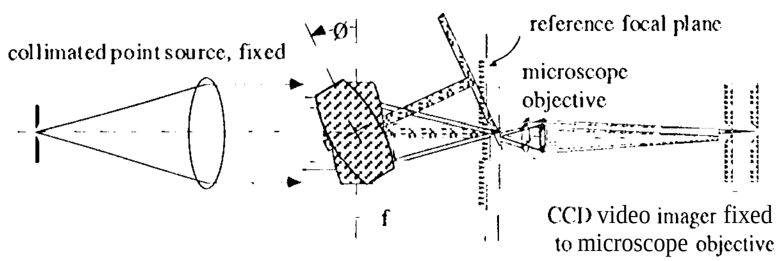
MISR camera imaging performance is specified in terms of MTF. That is, camera MTF at 23.8 c/mm (the Nyquist frequency of the CCD detector) must exceed 0.24 over the entire operational parameter space of field, wavelength & temperature. This performance requirement is then broken down into MTF requirements on bins, CCD array & interface components.

Having settled on MTF as the standard image performance metric, the task then became one of implementing an MTF measurement capability within the thermal vacuum and other constraints described above.

The "virtual nodal bench" architecture schematically shown in the figure above meets the requirements while it avoids the complexities of moving collimators and "T bars". The OCB was built by the Optikos Corp. of Cambridge, MA and resembles most closely the traditional nodal bench wherein the lens under test (LUT) is longitudinally translated until the spot formed in the image plane shows no transverse motion in the presence of rotations of the LUT about the nodal point.

SHOWING NODAL BENCH GEOMETRY

lens under test (LUT) mounted on T-bar



T-bar-driven piston of microscope objective & CCD = f [secØ -1]

In the traditional nodal bench, as shown in the figure above, the T-bar maintains the microscope objective focussed on the focal plane of the LUT. in our "virtual nodal bench" system, this is achieved by coordinating the motorized translation of the microscope with the motorized rotation of LUT.

4. THERMAL CONSIDERATIONS

In order to remove systematic errors, it is important to keep the metrology equipment at constant temperature while the (thermally blanketed) LUT or CUT alone is conductively driven to the temperature of interest. This is achieved in the OCB by means of a unique thermal lens mount described below:

LUT's & CUT's are mounted on an aluminum thermal header similar to the real thermo-mechanical interface on the spacecraft. Liquid and gaseous nitrogen driven through this thermal header provide direct conductive cooling or heating of the LUT or CUT.

This thermal header is in turn carried on the gimbal on a thin, titanium tube providing a high degree of thermal isolation between the (room temperature) metrology and the LUT or CUT. Thus the LUT or CUT can be quickly driven to a temperature setpoint while the balance of the test hardware (gimbal, microscope, collimator, fold mirrors, test bench) remains at room temperature.

5. SYSTEMATIC ERROR SOURCES IN THE OCB

A variety of systemmatic errors must be treated before accurate, repeatable imaging performance measurements can be made. These errors include . . .

- finite pinhole size

Optikos software corrects for finite pinhole size.

• test wavefront collimation

Having a large de-magnification between collimator and LUT makes for a system very forgiving of collimator defocus errors: An autocollimation telescope measures source pinhole defocus error of 225 pm; this in turn maps into a wors[-case defocus offset of 3 μm in the LUT; small compared to tbc depth of focus of our f/5.5 LUT's.

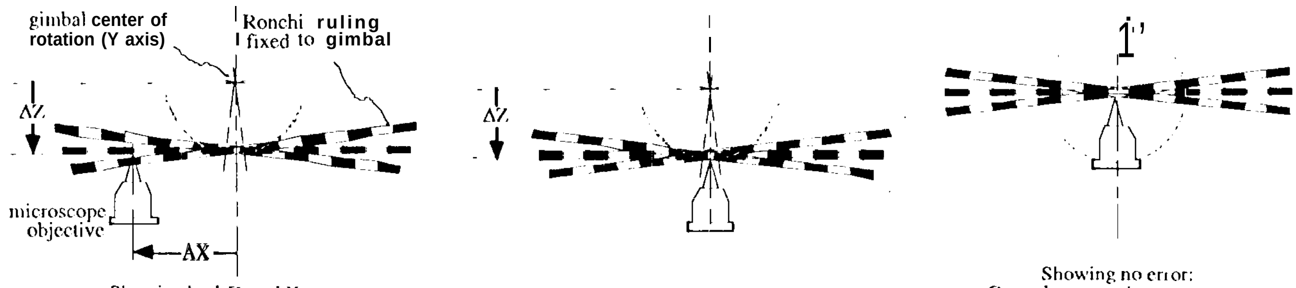
• lens/camera mount pointing (boresight) errors

A piano mirror mounted on the lens mounting surface of the gimbal is used to retroreflect the collimator beam. That is, that gimbal position which causes the collimator output to be accurately retroreflected back into the source pinhole is defined to be the on-axis or boresight or zero field angle of lenses or cameras mounted on the gimbal. Pointing is established to better than 0.002 degrees which is roughly equivalent to a fraction of the diffraction-] imited spot size.

• location of gimbal axis of rotation

A Ronchi ruling located in the vicinity of the intersection of the gimbal rotation axes was successfully utilized to establish a global coordinate system encompassing the entire object and image space. location of this intersection point is crucial to the absolute, unambiguous determination of an optimum LUT focal plane. The procedure used is schematically shown in the following figure:

Showing method for locating gimbal relation axis



Showing both Z and X errors: Under gimbal rotation, all bars move; one side of the field more than tbc other

Showing only Z error: Central bar moves least

Showing no error: Central bar remains stationary; gimbal rotation axis located

Surveying of the metrology components begins by installing a Ronchi ruling in the gimbal in the vicinity of the rotation axes. The rulings arc installed in a vertical orientation nominally parallel to the crosstrack or vertical rotation axis of the gimbal. As the gimbal is made to oscillate, wc view the 10 micron wide rulings with the MTF head video microscope. First, the MTF head is translated in the X direction until the central bar moves the least. The ronchi ruling is then translated longitudinally inside the gimbal until a "null bar" is identified; this ruling line coincides with the gimbal rotation axis and enables both the MTF X and Z position zeroes to be established.

• measurement & correction of lens decentration errors

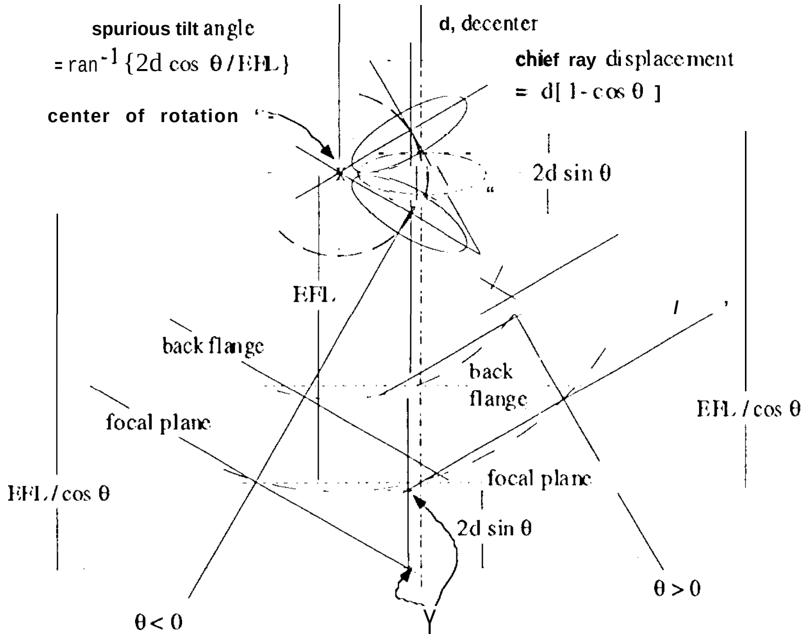
When the alignment & offsets of the MTF stage arc established, absolute decentrat ion of the LUT in tbc gimbal can then be determined. 'l'his enables the spurious tilt effects resulting from the decentration error to be removed from subsequent measurements.

That is, when a LUT is installed, tbc X intercept of the. chief ray may be read directly from the MTF head transverse X position encoder as LUT decentration. This in turn allows the. systemmatic/spurious tilt error τ to be determined according to the following relation:

$$\text{spurious tilt } \tau = \tan^{-1} [2d \cos\theta / EFL]$$

For example, a decenter d = 250 μm and a lens with EFL = 59 mm and ± 14.9 deg field angle results in a spurious tilt τ of 0.47 deg. See Figure below:

Taking MTF data cm this sytemmatically tilted reference plane then enables intrinsic lens tilt (i.e, real tilt of the focal plane relative to the lens barrel interface flange) to be read directly from the MTF "haystack" (Section 6.3) data.



focal points @ plus & **minus** field positions

- gimbal position & velocity errors

Lens MTF measurements require primarily gimbal *position* stability -0.0010 degrees which is easily met by the gimbal servo control sytem which is stable & accurate to 0.0003 degrees. Camera testing -- particularly camera geometric distortion mapping -- requires gimbal *velocity* stability -1 0% which again is readily met by the gimbal.

- MTF stage alignment & calibration

MTF stage alignment basically has to do with a rendering of stage translation vectors and offsets relative to both the beam propogation vector and the gimbal axes. When complete, the MTF head Z axis is parallel to the beam propogation direction and the offsets of X & Y axes arc rendered relative to the gimbal axes to better than 10 microns.

- microscope achromatization

The expected high degree of achromatic correction in the 40X Nikon apochromat was experimentally verified to be better than the 5μm encoder resolution and thus contributes no systematic error to the MTF measurements.

- detector background

With the fiber lightsource feeding the pinhole shuttered, the detector background/ dark current is digitally subtracted from all MTF measurement frames

- testing telecentric lenses on a nodal bench

In a telecentric lens design the chief ray is normally incident on the focal plane at ail field angles. However, in a nodal bench test configuration, the pinhole image will move transversely as different focal planes arc explored. This effect necessitates continuous tracking and background corrections for accurate, consistent MTF readings.

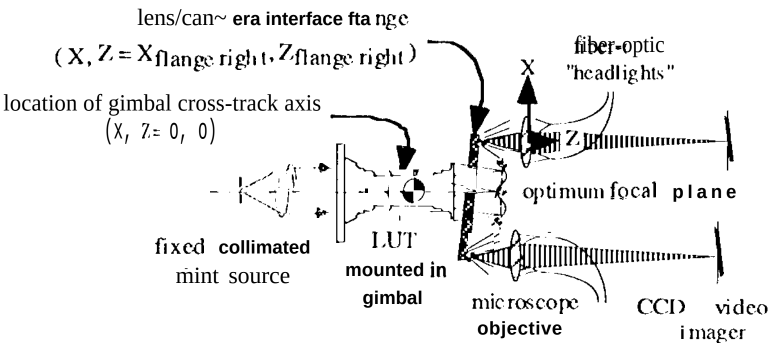
6. LENS MEASUREMENTS

6.1. Identification of nodal point ("gassing") in order to make consistent measurements of MTF at various field positions, the LUT must be longitudinally fixed inside tbc gimbal rotation ring so that the rear nodal point falls on the gimbal rotation axis. After so doing, transverse motion of the spot is minimized under gimbal rotations; only the expected sec$\varnothing$ -1 (a.k.a. "t-bar") longitudinal focus shift is seen. An automated measurement routine transforms these transverse spot displacements into a longitudinal lens position correction value.

6.2. Identification of reference focal plane relative to mechanical features

Determining the distance from the optimum focal plane to the lens/can}cra interface surface is accomplished using the non-contact coordinate measuring machine (CMM) -like capability of the OCB: This capability (see schematic figure below) obtains from the use of optical fibers brought into the back side of the microscope objective. Light emerging from the ends of the fiber passes through the microscope objective flooding the object plane conjugate to the CCD in the video microscope. in so doing, opaque but otherwise highly scattering machined surfaces can be clearly imaged. Since the video microscope is carried on a motorized, position-encoded stage, wc gain complete knowledge of lens focal plane position relative to a hard mechanical interface.

SHOWING NON-CONTACT CMM CAPABILITY OF MTF BENCH

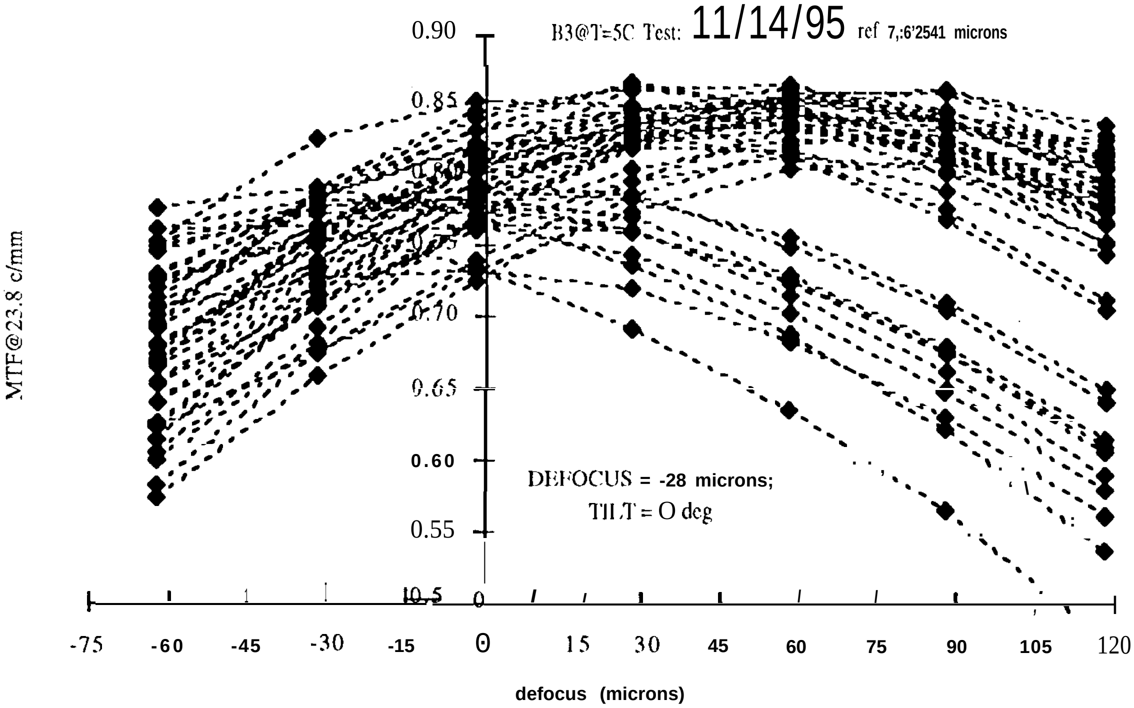


6.3. Collection of MTF, distortion & transmission measurements

A lens MTF measurement is obtained from a Fourier transform of the point spread function. Optikos's standard commercial VideoMTF software is used to transform magnified PSF images into MTF measurements in two orthogonal directions.

The optimum lens focal plane is identified with respect to wavelength, focal plane, FOV, orientation and temperature. Of the many criteria that might be used, wc have chosen a "minimum MTF" criteria for identifying the optimal" focal plane. That is, we will identify the plane (or volume) on which MTF will always exceed the minimum MTF value for any wavelength, field position, orientation or temperature simultaneously.

This criteria is straightforwardly visualized when wc plot MTF vs. focus position. Superimposing through-focus curves for each wavelength, field position, orientation case -- a total of 40 curves -- the focal plane or volume in which the minimum MTF criteria is met can be seen. An example "haystack set" for one temperature is shown below.



6.4. Shimming & camera assembly.

once the optimum lens focal plane is identified with respect to the lens/can~era head interface flange, the appropriate shims can bc fabricated and installed to insure that camera head will be located inside the above-dcscribcd volume.

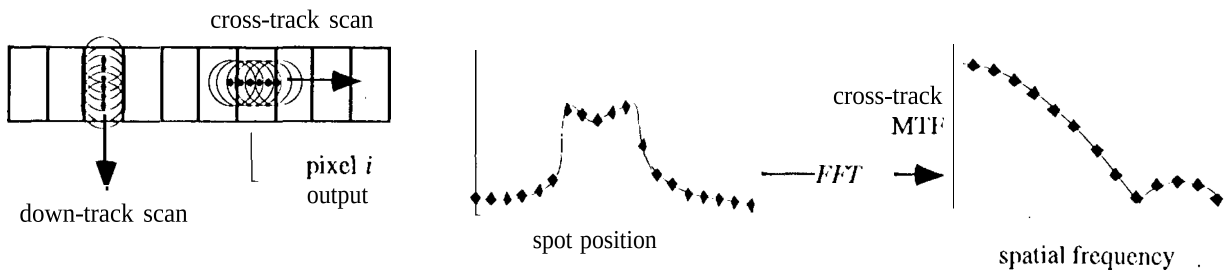
Following shimming, the lens returns to the OCB as a camera assembly for camera level testing.

7. CAMERA MEASUREMENTS

Catncra-level measurements include: 1) Identification of downtrack & crosstrack boresight errors; 2) MTF horizontal/crosstrack & vertical/dmvntrack measurements and 3) distortion ("pixel-theta") measurements. All of these measurements arc strongly dcpcndcnt on accurate gimbal positioning & motion.

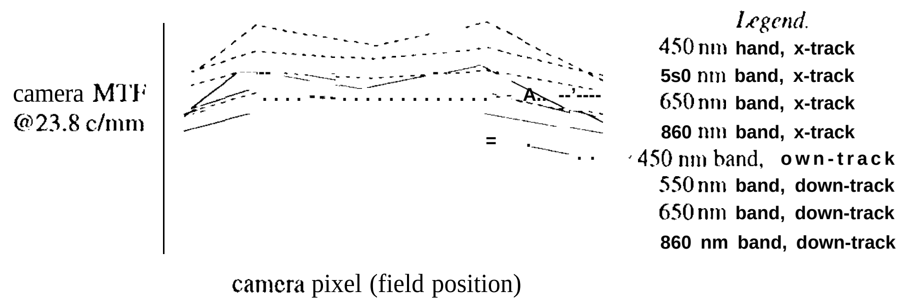
All camera testing is done using the unfiltered xenon light source and with unresolved pinhole targets. Since the focal plane is only partially filled by the four line arrays, the gimbal must bc slewed to direct the pinhole image onto a given detector pixel. At that point, the gimbal position encoders enable both cross-track & downtrack pointing errors to be read directly.

Camera MTF (in both crosstrack & downtrack directions) is measured by Fourier transforming the 128 point system PSF resulting from scanning an unresolved spot across (or down) a given pixel. A typical system PSF and it's Fourier transform (FFT) arc shown in the figure below:



Showing measurement of camera MTF

From the MTF curve, the MTF value at 23.8 c/mm, the spatial frequency of interest is extracted and combined with the same values taken at other field positions & wavelengths to produce a plot such as that shown in the figure below.



Showing MISR camera MTF vs. field position

These experimental results arc consistent with the spatial-frequency-wise product of component MTF's, namely, lens MTF measurements (described above) with CCD MTF measurements. The latter are described in another paper from the.sc same Proceedings entitled "Lloyd's mirror measurements of MISR CCD's", Hochberg, et al.

A detailed description of the camera distortion measuring methodology can be found in a paper in these same proceedings entitled "Distortion calibration of the MISR linear detector arrays", Korechoff et al.

8. SUMMARY

The OCB has proven to be an extremely efficient apparatus for quantifying imaging performance of tbc MISR lenses & cameras over a large parametric space including space-cnviromncntal conditions.

9. ACKNOWLEDGEMENT

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